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The polarization interaction of plasma flows in a transverse magnetic field was studied, using plasma guns and special targets. A polarized plasma stream, moving in a transverse field, decreases in density at increase in field strength. On frontal collision of oppositely directed plasma flows, strong deceleration and even complete arrest takes place. In contrast to Coulomb interaction, plasma interaction does not take place in the depth of the plasma jets but in their frontal region, leading to turbulence and vortex formation. Presumably, this interaction takes place also in the absence of Coulomb interaction. Photographs of plasma glow and oscillograms for both types of interaction are given.

INTRODUCTION

AUTHOR

The study of the interaction between colliding plasma flows is of practical interest in connection with the thermalization of plasma flows. A directed particle velocity as high as 10^6 m/sec, which is attainable with modern plasma guns, may be sufficiently high to obtain high-temperature plasma, provided the motion of the clusters is completely arrested.

The present work is a continuation of our study of the conditions of interaction of high-speed plasma flows with conversion of the kinetic energy of

* Numbers in the margin indicate pagination in the original foreign text.

their directed motion into thermal energy. The Coulomb interaction between particles of the colliding flows can of course obviously not be used for this purpose, since to obtain the high temperatures desired (10^8 °K) as a result of randomization of the velocities would require a plasma density of 10^{18} cm^{-3} for deceleration to occur over a length of not more than 1 m. Existing plasma guns cannot do this.

It therefore seems to us both interesting and useful to investigate the so-called polarization interaction of plasma flows moving across a magnetic field.

The motion of plasma in transverse magnetic fields has already been suc-cessfully studied by a number of authors (Bibl.1-4). In their experiments, however, they failed to pay sufficient attention to the necessity for ensuring a strictly frontal collision between the plasma clusters, which exerts a de-cisive influence on the effectiveness of the deceleration.

1. Description of the Equipment

The experiments were made on the apparatus shown in Fig.1. A chamber 20 cm in diameter was placed in a longitudinal magnetic field induced by coils fed by a DC generator. The field could be varied from 0 to 0.5 teslas. In the central section of the chamber, eight conical plasma guns with insulating cones of Plexiglas (Bibl.5) were mounted along the circumference. Plasma was formed in the gun by the discharge of a 3 μf capacitor between the central electrode at the vertex of the cone and an annular electrode at its base. The duration of the discharge was 6 μsec. The plasma consisted of a fast and a slow component, with respective velocities of 8×10^4 and 3×10^4 m/sec, at a potential of 4 kv in the gun, and contained ions of hydrogen, carbon, oxygen, and nitrogen.

Depending on the experimental conditions, the guns could be attached either

directly to the chamber, within the magnetic field region, or placed out- /1418

side the magnetic field and connected with the chamber by means of plasma

guides (copper tubing 5 cm in diameter). To keep the diffuse magnetic field

from penetrating the plasma guide, the guides were shielded by iron screens. A

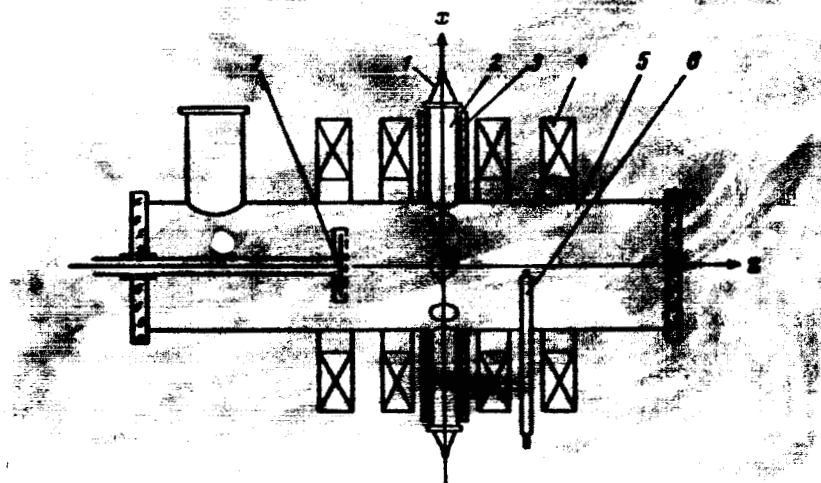vacuum of $1.33 \times 10^{-3} n/m^2$ was established in the chamber.

Fig.1 Schematic Sketch of the Device
1 – Plasma source; 2 - plasma guide; 3 - magnetic
screen; 4 - coil; 5 - vacuum chamber; 6 - probe
collector

The plasma was diagnosed by the aid of superhigh-speed photography and by

photographing the integral glow of the plasma, double electrostatic probes, and

flat probe collector, and special targets which lit up under the impact of

plasma.

2. Motion of Plasma across a Magnetic Field

Bostick (Bibl.1-3) and others (Bibl.4-7) have already shown that plasma

jets can move across a magnetic field. When a plasma stream does move in this

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way, there arises in it an electric field E, perpendicular both to the velocity V_0 and the magnetic field B. This electric field is connected with the formation of surface charges of a density of

$$\sigma = \frac{(\epsilon - 1)[V_0 B]}{4\pi c},$$
(1)

where ϵ is the magnetohydrodynamic dielectric constant of the plasma.

A study of the motion of plasma flows across a magnetic field performed in the Safronov laboratory (Bibl.8) showed that a jet of plasma penetrating into the region of a transverse magnetic field gradually loses its density in the direction of motion on account of the loss of the lighter component of the plasma along the direction of the magnetic field. The mechanism of the process by which the velocity $V_0 \perp B$ is transformed into the parallel velocities B is still unknown, but is most probably connected with the formation of polarized layers of density σ.

In contrast to that work (Bibl.8), in which plasmoscopes were used, we studied the motion of the plasma jets by the aid of special targets, described elsewhere by us (Bibl.6). Figure 2 shows photographs of these targets, arranged at various distances from the plane of injection and positioned perpendicularly to the direction of the magnetic lines of force. They were placed at the following distances from the plane of injection: a - z = 4 cm, b - z = /141̲9̲ = 7.5 cm; c - z = 15 cm, and d - z = 23 cm. The injection was from a single gun in the direction shown by the arrows on each target. The magnetic field in these experiments was 0.25 teslas. As will be seen from Fig.2, the plasma injected across the magnetic field also moves longitudinally along the magnetic field.

The propagation of plasma along the magnetic field is symmetric on both

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sides of the plane of injection. The traces of the plasma impacts on the tar-
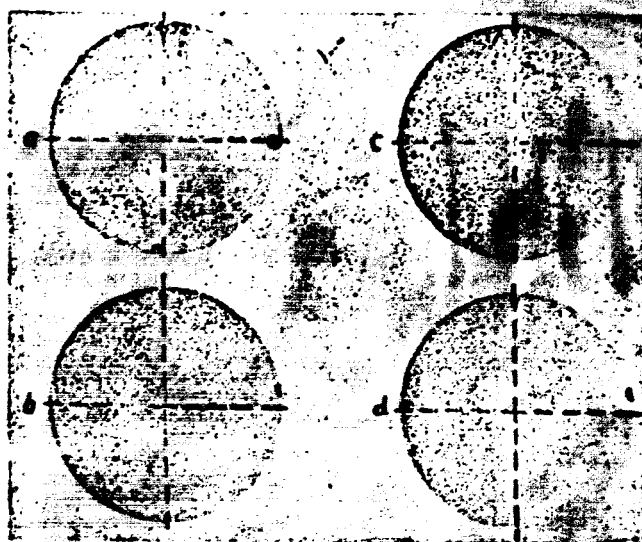gets shown in Fig.3 indicate this. Target a in Fig.3 was placed in the plane

Fig.2 Photographs of Targets Lit Up by Impacts of Plasma.
The targets were arranged perpendicularly to the mag-
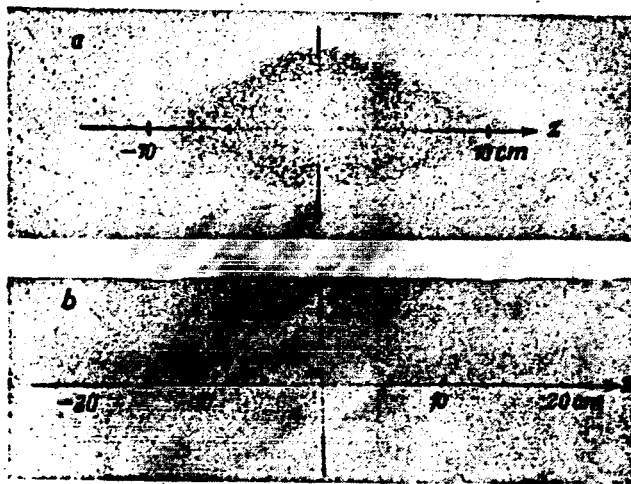netic field at various distances from the plane of
injection.

Fig.3 Photographs of Targets Arranged Parallel
to the Magnetic Field

passing through the axis of the chamber and perpendicular to the direction /1420

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of the injection. Target b in Fig.3 was aligned along the chamber wall, opposite the point of emergence of the plasma guide. It will be seen from the photographs that the traces of the impacts of the plasma on the target are markedly elongated along the z-axis, symmetrically with respect to the plane of injection.

The measurements on the targets were made at high gun potential (U_g = = 12 kv, n > 10^{13} cm^{-3}), since a very long exposure was required because of the small area of the plasma.

3. Frontal Injections of Plasma from Several Sources across a Magnetic Field

In earlier experiments (Bibl.6) we investigated the interaction of opposite or frontal plasma flows when injected into a slit between opposite magnetic fields. The experimental conditions were so chosen that Coulomb interaction took place (low velocity and high density of the particles in the colliding bunches).

The object of the present work was to study the possibilities of complete arrest and thermalization of high-speed opposing plasma flows. Obviously, a solution of the problem demanded search for the conditions of strong interaction of opposing flows of plasma, excluding Coulomb interaction. Coulomb interaction cannot arrest the plasma bunches of high velocity and insufficient density, produced by our present plasma sources. Therefore, we started investigating so-called polarization interaction.

If two plasma flows move in opposite directions across a magnetic field, then electric polarization fields of opposite signs are formed in them. When the clusters collide, these fields will be mutually canceled, the drift across

the magnetic fields should stop, and the velocity of translation of the ions $\pm v_0$ will be converted into pure orbital motion. In the region of interpenetration of the plasma jets, there should obviously occur a marked increase in plasma density and an accompanying expansion along the direction of the magnetic field.

The experiments to be described below were made on plasma bunches in which the possibility of Coulomb interaction between colliding particles was excluded (the density of the particles being less than 10^{13} cm^{-3}).

Figure 4 shows photographs of the integral glow of plasma produced at a gun potential of 4 kv, i.e., at a plasma density of the order of 10^{12} cm^{-3} (the density was estimated from the blocking of 3-cm waves). Figure 4a was taken in the absence of a magnetic field. No interaction of the plasma flows was noted in this case. With increasing transverse magnetic induction of the field, the interaction becomes more intense (Fig.4b, c, d, taken at 0.05, 0.35, and 0.48 teslas, respectively). In these cases the plasma flows, on collision, stop their motion and send out lateral peaks and vortices. Such vortices and turbulence were not observed in our earlier experiments (Bibl.6), where Coulomb interaction played the major role (Fig.5). These peaks may or may not reach the chamber walls, depending on the gun potential, the magnetic field strength, and the accuracy of frontal collision between the clusters. At low gun potential and strong magnetic field, the peaks will not reach the chamber walls (Fig.4c and d), while, on the other hand, with a weak magnetic field and high gun potential, the peaks do strike the chamber wall. When only the edges of the plasma jets collide, the jets break up to the point of contact and thereafter move at an acute angle to their original direction.

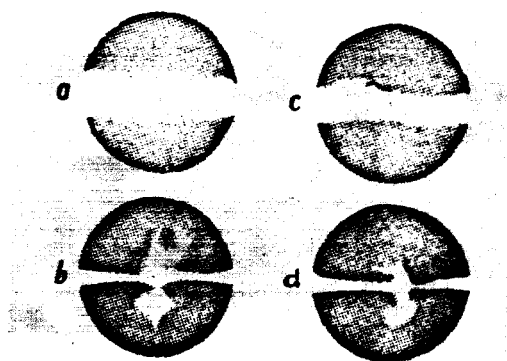Figures 6a and b show photographs of the integral glow of plasma injected

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Fig.4 Interaction of Plasma Injected by
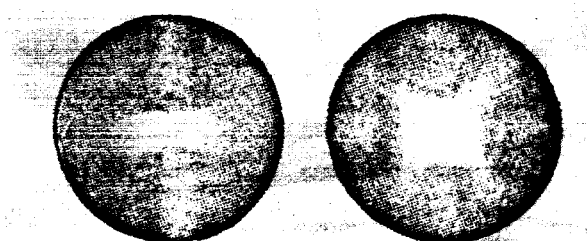Two Guns (Integral Glow).

Fig.5 Typical Photographs of Plasma Glow
in Coulomb Interaction.
Injections from two and four guns in the
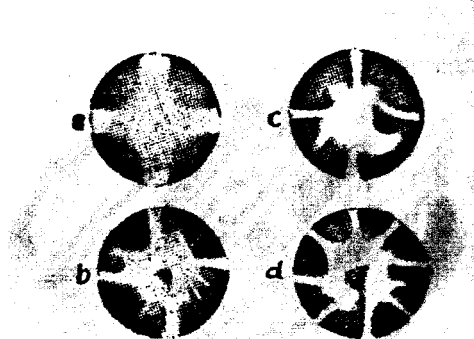absence of a magnetic field.

Fig.6 Interaction of Plasma Injected by
Four and Eight Guns (Integral Glow).

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by four guns in the absence of a magnetic field, and across a field of in-

duction 0.33 teslas (U_t = 4 kv). Interaction is observed only in the presence

of the magnetic field (Fig.6b). If the plasma moves in a curvilinear trajec-

tory and there is no frontal collision, then when plasma is injected from sev-

eral sources, a space close to the axis will remain unfilled with plasma. Typi-

cal photographs of this case, taken at a gun potential of 5 kv and magnetic in-

duction of 0.33 teslas, are given in Fig.6c and d. (Injections were from four

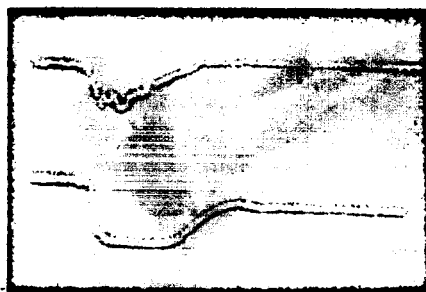and eight guns.) Comparing the photographs of plasma interaction in the trans-

Fig.7   Oscillograms of Signals from a Rogowski
Yoke (Upper Trace) and a Magnetic Probe
(Lower Trace)

verse magnetic field with those taken in the case of Coulomb interaction (see

Fig.5), we note that interaction in the former case is of a superficial charac-

ter and does not go through the volume, as in the latter case.

The azimuthal induced ring current flowing in the plasma was measured by

the aid of a Rogowski yoke. The direction of this current was such that it in-

creased the external longitudinal magnetic field B_0 inside the plasma ring. The

increase in the magnetic field was registered by a magnetic probe placed on the

axis of the chamber, in the center of the ring, in the plane of injection.

Figure 7 gives oscillograms of the integrated signals from a Rogowski yoke

(upper trace) and a magnetic probe (lower trace), taken at induction of the ex-

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ternal magnetic field B_0 = 0.01 teslas on injection by eight sources. Figure 8
shows graphs of the amplitude of the additional field ΔB_z and the azimuthal
current I_φ. These curves have the following features: ΔB_z and I_φ at first in-
crease linearly with B_0, pass through a maximum, and decline as $\sim \frac{1}{B_0}$. With
increasing gun potential, the maxima of the curves are shifted toward the side
of greater B_0. An increase in the magnetic field on the axis was observed on
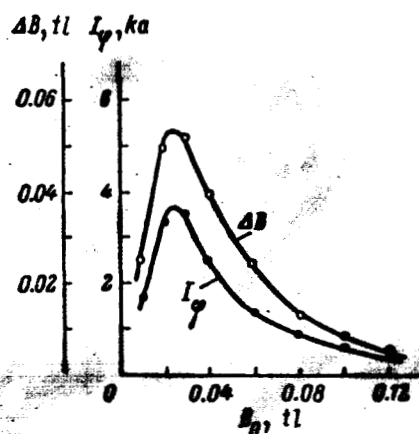injection by eight and four guns.

Fig.8 Plot of ΔB_z and I_φ against B_0
for Injection from Eight Sources
at U_g = 8 kv.

The interaction of polarized plasma is also confirmed by measurements with
a double electrostatic probe. The probe was inserted into the chamber to a
distance of 15 cm from the plane of injection and could be moved along the di-
ameter of the chamber. Measurements with the probe showed that the boundary of
the glow coincided with the actual boundary of the plasma, since the probe gave
no appreciable signal when it was outside the glow region.

Figure 9, left, shows photographs of the plasma glow while Fig.9, right,
gives oscillograms of the saturation current of the double probe corresponding
to these photographs. On the lower traces of the oscillograms we superposed a

sinusoid of 200 kc frequency for calibration of the sweep time. The arrows in-
dicate the direction of injection. The oscillograms and photographs were made
at B_z = 0.25 teslas and U_g = 4.7 kv. On the photographs of the glow the shadow
of the probe can be seen. The plasma was injected 15 cm beyond this point. The
photographs of the glow and the oscillograms of Fig.9a, b, c correspond to /14/22
the probe positioned on the axis of the chamber, while in Fig.9d the probe was
2 cm from the wall opposite the plasma source.

As shown by the oscillograms, the plasma injections from a single gun
(Fig.9a, b) give a considerably shorter signal from the probe than an injection
from two guns (Fig.9c), provided the probe is close to the chamber axis. A pro-
longed signal is likewise obtained when the probe is close to the chamber wall
and the injection is only from a single gun on the opposite side (Fig.9d). If,
however, the injection is from two guns, or from one gun on the same side near
the probe, then the signal is short, like those of Fig.9a and b. In other
words, the probe gives a prolonged signal when it is in the expanding plasma
cloud.

As was clear from the target measurements, when the plasma enters the cham-
ber it is propagated not only across the field but also along the field. On
the basis of work by others (Bibl.8), we may postulate that the fast and light
components of the plasma move along the magnetic field, while the heavy and
slower components, after crossing the field, impinge on the opposite wall of
the chamber and are then propagated along it. That is why, for a one-gun injec-
tion, the probe, if it is far enough from the plane of injection, gives a short
signal produced by the fast component, while the signal from the probe near the
wall against which the plasma impinges is produced by the slow and heavy com-
ponent being propagated along that wall. On injection by two opposing guns, the

fast component, as before, moves at once along the magnetic field, while the slow component is retarded by the opposing flow of plasma near the axis, and thus does not reach the opposite wall but is propagated along the chamber in the region of the axis instead of at the wall. The probe on the axis in the region of the plasma cloud therefore gives a long signal, while a probe outside the region of interaction gives a short one.

Besides the double probe we also used a collector probe in the form of a disk 10 cm in diameter with a screen in front of it.Between the screen and the disk a potential of the order of 30 v was applied (region of saturation of the probe current). The plane of the probe was placed perpendicular to the chamber axis, as shown in Fig.1. The probe could move along the chamber axis and collected the ions moving in opposite direction to it on the area $s = 78$ cm^2. The current I on the probe was considered proportional to envs, where e is the charge of an ion, n the density, v the velocity, and s the area of the probe.

Figure 10 shows typical oscillograms of the probe current and the corresponding photographs of the glow of the plasma injected from one or two guns. ($U_k = 4.3$ kv, $B_z = 0.28$ teslas, distance between probe and injection plane 30 cm, time marks at 20 μsec intervals). The oscillograms show that, on injection from a single gun (Fig.10a, b), the duration of the signal was considerably shorter than on injection from two guns (Fig.10c). At first, until full amplitude was attained, the height of the signal was approximately equal to the sum of the separate signals from each gun, for the two-gun injection, but the signal in the "tail" on injection from two guns considerably exceeded the sum of the signals from each gun.

It should be noted that, in contrast to the double probe, which collects the ions from the entire surface and in which the saturation current is propor-

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tional to the ion density at a given point, the current on a probe of greater

diameter is likewise proportional to the cross-sectional area of the plasma jet

impinging on the probe, if that area is less than the area of the probe. For

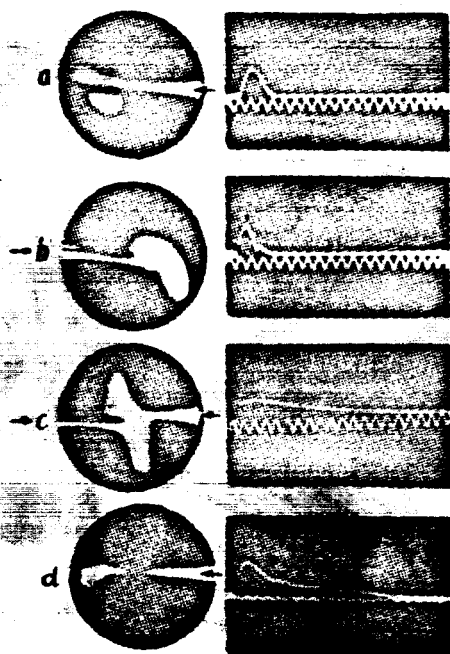this reason the fact that the signal amplitude on injection from two guns equals

Fig.9 Photographs of Integral Glow
of Plasma (Left) and Corresponding
Oscillograms of the Saturation Cur-
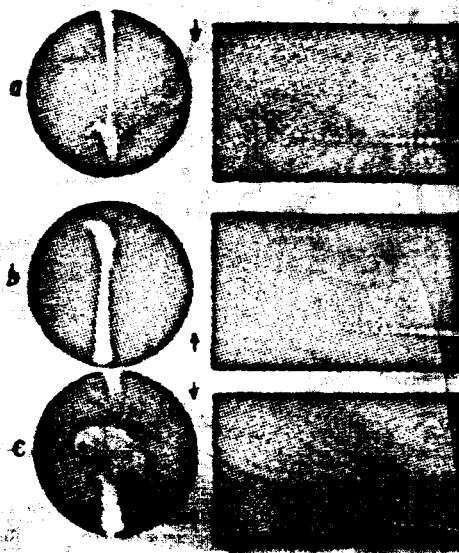rent of the Double Probe.

Fig.10 Photographs of Integral Glow
and Oscillograms of Saturation Cur-
rent of the Collector-Probe.
a and b – injection from one gun;
c – simultaneous injection from two
guns.

the sum of the amplitudes of the signals on injection separately from each /1423

gun suggests that the fast component of the plasma, moving along the magnetic

field, had velocities directed almost parallel in both jets and did not undergo

interactions, so that consequently the probe registered twice the number of ions

reaching it from the two separate guns.

However, the slow component which, in the case of separate injections moved

across the field and hardly reached the probe at a considerable distance from

the injection plane, underwent interaction in the case of simultaneous injection and likewise began to move along the magnetic field in the axial region, causing the appearance of a long "tail" of the probe signal.
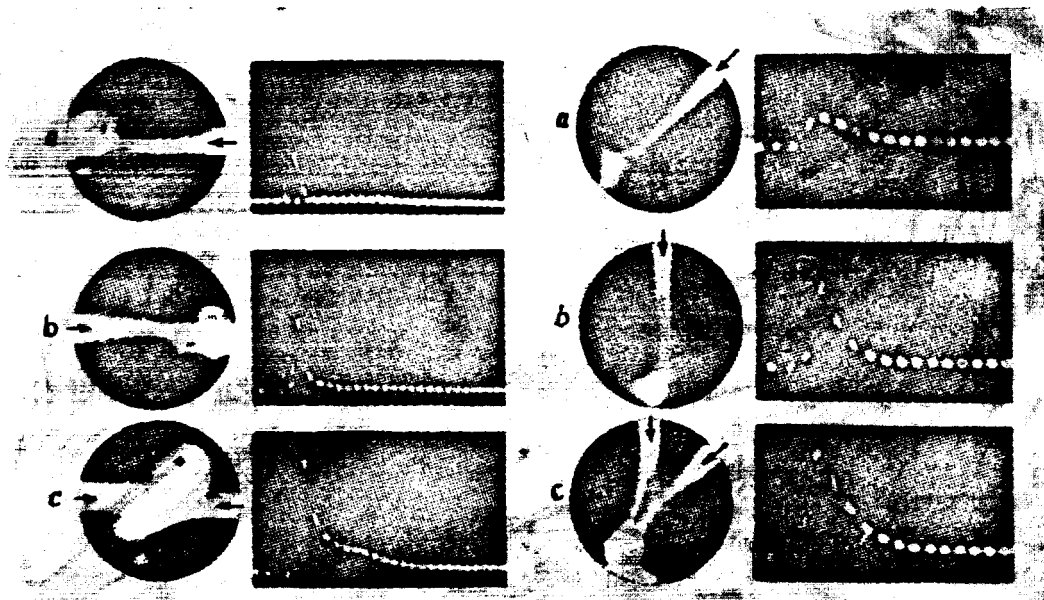

Fig.11 Photographs of Integral Glow and Oscillograms of Saturation Current of Collector Probe.

a and b - injection from one gun; c - injection from two guns (not frontal collision)

Fig.12 Photographs of Integral Glow and Oscillograms of Saturation Current of Collector Probe.

a and b - injection from one gun; c - injection from two guns at an angle of $\pi/4$ radians

If the plasma clusters do not collide frontally, but merely graze each other's edges, then the duration and height of the "tail" are considerably less than on frontal collision, as will be seen from Fig.11c. There is even less difference between the duration of the probe signals from one-gun and two-gun injections, if the injected plasma flows from the two sources meet at a small angle. Typical oscillograms and photographs of this case are shown in Fig.12. Summation of the signals of Figs.12a and b gives a curve that almost coincides with the oscillogram of Fig.12c over the entire length of the signal. This indicates that the plasma jets did not undergo interaction here either.

We note that there is a simple explanation for the experimentally found dependence of the compression ΔB_z of the field on B_z (Fig.8). As already mentioned, a polarized plasma jet, moving in a transverse magnetic field, decreases in density, and this decrease is greater the stronger the field. It is therefore only natural that, in strong fields, an annular induction current should be formed in a less dense plasma, and that on still further increase in the field the plasma jets should cease to meet altogether.

In the region where the intersection of plasma bunches commences, a peculiar theta pinch is formed, with a current layer within the plasma, i.e., in the region where the plasma-vacuum boundary has a positive curvature and, consequently, also magnetohydrodynamic stability. The "external" boundary of the plasma is completely undefined and is located in a region with negative curvature, explaining the formation of plasma flares and tongues (Fig.6). It will apparently be possible to suppress these troughlike instabilities by the application of additional fields $\pm B_\theta$.

CONCLUSIONS

The present experiments show that, on frontal collision of oppositely directed plasma flows in a transverse magnetic field, these flows undergo strong braking and even complete arrest of motion in their original direction. In contrast to Coulomb interaction, the interaction does not take place in the depth of the plasma streams, but in their frontal regions, and is of a turbulent nature that forms complex vortices.

It is important to note that this interaction presumably occurs even in cases where there is no Coulomb interaction.

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